Russian Olive Biology, Invasion, and Ecological Impacts in Western North America

by Gabrielle Katz

INTRODUCTION: The United States Army Corp of Engineers (USACE) Ecosystem Management and Restoration Research Program (EMRRP) is supporting a nationwide effort to address the impact of invasive woody plant species on ecosystem restoration, and more specifically, to determine mechanisms to address the most regionally prevalent invasive species impacting restoration activities. The research effort has four objectives: (1) Identify the suite of invasive woody riparian plants that are most problematic to USACE ecosystem restoration efforts, (2) develop guidelines that suggest thresholds for when and where on the landscape funds should be spent to control invasive woody plants, (3) determine the most efficient and ecologically effective spatial configuration for woody invasive riparian plant removal on USACE managed lands, and (4) investigate how faunal communities respond to various spatial control methods for woody invasive plant removal in densely vegetated riparian habitats. This technical note supports the first objective and focuses on Russian olive (*Elaeagnus angustifolia* L.), a species that invades riparian ecosystems of the western United States and can be problematic for ecosystem restoration efforts.

Russian olive (*Elaeagnus angustifolia* L.) is a non-native, nitrogen-fixing tree or multi-stemmed shrub that is now one of the most common woody species in western U.S. riparian ecosystems. It is native to southern Europe and central Asia, but was introduced to North America by the late 1800's or early 1900's (Katz and Shafroth 2003). During the twentieth century, it was promoted and planted widely for wildlife habitat and windbreaks (e.g., Borell 1951), and it subsequently spread from such plantings to become naturalized in riparian areas in much of western North America. In a study of 475 stream gauge sites distributed throughout the western U.S., Friedman et al. (2005) found Russian olive to be the fourth most frequently observed woody riparian species, and the fifth most dominant (on the basis of cover). Native cottonwoods (*Populus* sp.) and willows (*Salix* sp.) were the most commonly observed and abundant woody species in these systems, while non-native tamarisk (*Tamarix* spp.) was the third most frequent and dominant species. Although regional dominance by tamarisk has been noted for decades, the prevalence of Russian olive has been recognized much more recently. Furthermore, Russian olive is likely to increase in importance in western U.S. riparian ecosystems as it continues to spread from plantings and established naturalized populations. Given this context, effective management and restoration of riparian ecosystems in the western U.S. requires knowledge of Russian olive biology, ecology, and ecosystem impacts.

The purpose of this technical note is to synthesize and assess the current scientific information on Russian olive, with a focus on topics relevant to the structure and function of invaded riparian

ecosystems in western North America. A diverse and growing number of studies have documented various aspects of Russian olive biology, ecology, ecosystem impacts, and management. Stannard et al. (2002), Katz and Shafroth (2003), and Zouhar (2005) reviewed some of the literature set forth in this technical note. However, an updated literature review is needed in order to summarize current knowledge and identify research needs. This review will build upon the previously published literature reviews and will therefore emphasize research published since 2005.

RUSSIAN OLIVE BIOLOGY AND ECOLOGY

Plant description. Russian olive is a member of the Elaeagnaceae family, which contains three genera, *Elaeagnus*, *Sheperdia*, and *Hippophae*. It is a small multi-stemmed tree or large shrub. Its wood is ring-porous with sap flow concentrated in large xylem conduits found in the outermost growth ring (Hultine and Bush, 2011). Russian olive has relatively high mean relative growth rate (1.61 mg g^{-1} day^{-1}), crop growth rate (= net assimilation rate x leaf area index; 1.73 g m^{-2} day^{-1}), leaf area index (1.65 m^2 m^{-2}), and leaf weight ratio (0.24 g g^{-1}) compared to other potential agro-forestry species tested in Khorezm, Uzbekistan (Lamers, Khamzina, and Worbes, 2006). Russian olive is deciduous with distinctive silvery green foliage. It produces fragrant, yellow flowers in the spring or early summer while single-seeded fruits mature during fall.

Russian olive is an actinorhizal species that forms a nitrogen-fixing symbiosis with actinomycetes bacteria of the genus *Frankia* (Katz and Shafroth 2003). As a result, Russian olive foliage exhibits high N content and low C:N ratio, compared to native cottonwoods (Table 1; Abelho and Molles, 2009; DeCant, 2008; Harner et al., 2009; Moline and Poff, 2008; Roggy, Moiroud, Lensi, and Domenach, 2004; Royer, Monaghan, and Minshall, 1999; Shah, Harner, and Tibbets, 2010; Simons and Seastedt, 1999).

Table 1. Published values of Russian olive and cottonwood foliar percent N and C:N ratio.

Species	% N	C:N ratio	
Russian olive	1.6	<30	
	1.8	--	Simons and Seastedt 1999
	2.25	20	Roggy et al. 2004
	2.58	18.92	DeCant 2008
	1.5	30	Moline and Poff 2008
	2.1	22.9	Abelho and Molles 2009
	2.1	25.1	Follstad Shah et al. 2009
	2.15	25	Harner et al. 2009
Cottonwood species*			
	<0.75	~70	Royer et al. 1999
	0.7	--	Simons and Seastedt 1999
	0.54	78.40	DeCant 2008
	0.6	70	Moline and Poff 2008
	1.4	33.7	Abelho and Molles 2009
	0.47	111.1	Follstad Shah et al. 2009
	0.49	113	Harner et al. 2009

Populus deltoides ssp. *monilifera* (Aiton) Eckenwalder (plains cottonwood; Simons and Seastedt 1999, Moline and Poff 2008); *Populus deltoides* Bartram ex Marsh. ssp. *wislizeni* [S.Wats.] Eckenwalder (Rio Grande cottonwood; Roggy et al. 2004, Decant 2008, Abelho and Molles 2009, Follstad Shah et al. 2009, Harner et al. 2009); *Populus trichocarpa* (black cottonwood; Royer et al, 1999).

Reproduction. Russian olive plants reach reproductive maturity at approximately 10 years old (Lesica and Miles, 2001). Flowers are produced in early summer and are insect pollinated. Fruits, single seeded drupes, ripen in late summer or fall, and birds, mammals, gravity, and water disperse them.

Russian olive is a prolific seed producer, at least in some years, and seeds can supply a persistent soil seed bank in invaded sites. Russian olive ground seed rain (seeds counted on the soil surface) was 27.8 ± 11.3 seeds/m^2 (mean $\pm$ SE) at invaded riparian sites in Canyon de Chelly National Monument, Arizona from May-June, 2007 (Reynolds and Cooper, 2011). Brock (2003) found that riparian soils (sieved soil samples) of invaded sites in northeastern Arizona contained an average of 415 seeds/m^2, of which approximately 38 percent appeared to be viable and contain live endosperm. Seeds are dormant when the fruits ripen and are dispersed, requiring a period of over-winter cold stratification for germination to occur (Guilbault, Brown, Friedman, and Shafroth, 2012). Russian olive seeding establishment occurs under a variety of environmental conditions (see below). Reynolds and Cooper (2010) observed that Russian olive seedling establishment declined with distance from adult tree seed sources along transects in Canyon de Chelly, Arizona, and argued that a slow rate of seed dispersal may limit its invasion into new areas.

Shade tolerance. Several experimental studies have demonstrated that Russian olive seedlings are more shade tolerant than seedlings of co-occurring woody riparian species. Katz et al. (2001) demonstrated that Russian olive seedlings could establish within undisturbed herbaceous vegetation in contrast to plains cottonwood, which requires physical disturbance for seedling establishment. In an experiment combining shade and water availability treatments, Reynolds and Cooper (2010) found greater seedling survival of Russian olive compared to both cottonwood and tamarisk under almost all treatment combinations, including low light levels. Consistent with these experimental studies, many field studies have documented Russian olive seedlings and adults growing in the understories of riparian gallery forests (e.g., Katz et al. 2005, DeCant 2008, Reynolds and Cooper 2010). Although Russian olive is shade tolerant, a few studies suggest that it performs better in full sun. Shafroth et al. (1995) found greater biomass of Russian olive seedlings grown in the sun compared to shade grown seedlings in an outdoor experiment in Colorado. Using tree rings, Lesica and Miles (2004) demonstrated faster growth rates of Russian olive juveniles and adults growing in full sun locations compared to those growing under the cottonwood canopy on three rivers in eastern Montana.

Water requirements. Although Russian olive tends to occur in wet areas of western landscapes (e.g., floodplains, wet meadows), it is not an obligate phreatophyte. Specifically, Russian olive does not require access to groundwater for survival and appears to be more drought tolerant than many native riparian species and the non-native tamarisk (Katz and Shafroth, 2003). Field observations suggest that Russian olive can establish on higher and drier geomorphic surfaces compared to cottonwood in the Great Plains (Katz, Friedman, and Beatty, 2005), and compared to both cottonwood and tamarisk in the Colorado Plateau (Reynolds and Cooper, 2010). In fact, isotopic analysis of water sources indicated that Russian olive established and survived for at least 15 years on terraces of Chinle Creek, Arizona where precipitation derived soil water was the only water source (Reynolds and Cooper, 2010). Hultine and Bush (2011) provided data demonstrating that Russian olive operated at a broader range of leaf water

potential than Fremont cottonwood at a site near Salt Lake City, Utah, indicating greater tolerance of dry conditions. On the other hand, Russian olive commonly occurs in wetlands and periodically inundated floodplain environments (e.g., Madurapperuma et al. 2013). Experimental studies have generally supported the idea that Russian olive is tolerant of a broad range of moisture conditions. This indicates that Russian olive seedling performance is not reduced under conditions optimal for cottonwood recruitment (Shafroth et al., 1995), and further indicates that Russian olive seedlings grow and survive better than cottonwood and tamarisk seedlings over a variety of moisture conditions including high and low water availability (Reynolds and Cooper, 2010). However, Russian olive does experience oxidative injury to leaf cell membranes under severe drought conditions and is not a truly xeric species (Gong, Zhao, Huang, Zhang, and Zhang, 2006). Russian olive is classified as a 'facultative' species in the Arid West and Western Mountain regions, suggesting that it occurs in wetlands and non-wetlands. Likewise, it also occurs as a 'facultative upland' species in other parts of its North American range, indicating that it usually occurs in non-wetlands, but may occur in wetlands (USDA, NRCS 2015).

Pathogens. Russian olive is susceptible to a variety of pathogens in North America. For example, in the northern Great Plains, Russian olive is commonly affected by the facultative fungal pathogen *Tubercularia ulmea*, which infects trees via physical injuries in the bark or frost damaged lenticels or buds (Jackson and Stack, 2002; Krupinsky and Walla, 1986). *T. ulmea* causes cankers in the bark of infected trees, and infection can lead to dieback or tree death. Although canker development is generally promoted by injury and stress to trees (e.g., freezing, moisture stress), short-term herbicide exposure did not promote canker development in one study (Jackson and Stack, 2002).

RUSSIAN OLIVE DISTRIBUTION AND SPREAD: Russian olive has a broad naturalized distribution within western North America ranging from northern Arizona, New Mexico, and Texas, northward to the southern Canadian provinces, and from eastern California, Oregon and Washington eastward through all western and mid-western states (Friedman et al. 2005; Nagler et al. 2011; Guilbault et al. 2012). At the continental scale, the distribution of Russian olive is associated with cold winter temperatures (Friedman et al. 2005; Guilbault et al. 2012). This association appears to be at least partly due to chilling requirements for seed germination and bud burst, with plant performance likely diminished near the southern distribution limit due to insufficient chilling (Guilbault et al., 2012).

Within its naturalized range, Russian olive tends to occur along rivers or in other areas of the landscape with supplemental moisture. Nagler et al. (2011) reviewed the literature on the distribution and abundance of Russian olive in the western U.S. and found that its abundance varied considerably among and within invaded river systems. Hamilton et al. (2006) used Feature Analyst to conduct a pilot mapping project of Russian olive at Salinas Creek, Utah, but did not explore environmental factors influencing its distribution. In one regional study, Ringold et al. (2008) found that Russian olive tended to occur on large rivers, and its occurrence on surveyed river reaches was associated with riparian disturbance and flow regulation. In a more localized study, Madurapperuma et al. (2013) used aerial photography and satellite imagery to digitize Russian olive stands within the Bismark-Mandan wildland urban interface in North Dakota to identify habitats vulnerable to invasion. They employed a variety of statistical methods to relate Russian olive abundance to land-use, land-cover, and soils data. Russian olive was

associated with silt loam and silty clay soil types, which occurred on the Missouri River floodplain, and areas of intermediate moisture availability (on a gradient from upland ecosystems to open water). Prairie grassland was the vegetation type least vulnerable to invasion, while sites with a mix of urban area, forest, and wetland were most vulnerable. However, the factors controlling Russian olive distributions at the river reach and site scales, including flow regimes and soil conditions, generally have not been well studied (Nagler, Glenn, Jarnevich, and Shafroth, 2011).

A few spatial models have been developed to describe the current distribution of Russian olive and predict its spread into new areas. Peterson et al. (2003) used Genetic Algorithm for Rule-set Production (GARP) ecological niche modeling to model the ecological niche and geographic distribution of Russian olive in its native range based on georeferenced occurrence data (41 locality points), and then projected its distribution onto North America. Their model predicted a very large potential range for Russian olive in North America. Hoffman et al. (2008) used maximum-entropy modeling to predict Russian olive distributions along the North Platte River, Nebraska. They collected location data in the field and obtained or calculated relevant environmental data layers (e.g., elevation, slope, aspect, land cover, distance from river, and soil texture). Within a 1.6 km buffer zone along the river, Russian olive distribution was most strongly associated with elevation, distance from the river, and soil percent clay. Their model predicted a relatively broad zone of potential Russian olive habitat in their study area. Jarnevich and Reynolds (2010) developed a habitat suitability model and map for Russian olive using datasets of presence locations within the western U.S., a variety of predictor variables (e.g., climate, topography, and distance to water), and maximum-entropy modeling. They found that at a coarse scale, the distribution of Russian olive was associated with distance to water; but at a finer scale, climate variables were more important. Their model predicted that Russian olive had suitable habitat further west than its current distribution, suggesting that it will continue to spread. Collette (2014) used maximum-entropy modeling georeferenced occurrence records from both the United States and Canada, on-ground and 'remote' (using Google Street View) occurrence road surveys near Kelowna, British Columbia, and a variety of predictor variables to model the predicted range of Russian olive in North America. Using the full Canada and U.S. datasets, Collette found additional predicted suitable habitat for Russian olive in southern British Columbia, and did not predict Russian olive to occur in some areas predicted by models based on U.S. occurrence data only. Russian olive was most likely to occur where the mean temperature of the coldest quarter was -0.9°C., and in areas with a soil pH of eight and soil salinity levels of 0 to ~1600 ppm. Collette advocated for vigilant monitoring of areas where Russian olive was predicted to spread. However, such predictions assume that Russian olive can spread into all areas of suitable habitat, and do not address the invasion process per se (i.e., propagule dispersal, establishment in the new area).

There has been very little study of the Russian olive invasion process. Katz et al. (2005) used tree ring analysis to determine the timing of Russian olive invasion into riparian areas of two rivers in eastern Colorado, but did not investigate the historic factors associated with invasion. In contrast, Reynolds et al. (2014) related the timing of Russian olive establishment in Canyon de Chelly, Arizona to historical change point events (i.e., local Russian olive planting, dam construction) and precipitation records. Although Russian olive was planted in the study area prior to the 1930s and upstream dams were constructed in the 1960s, massive invasion in the riparian zone did not occur until the 1980s. The authors hypothesized that invasion was triggered

by an episode of channel incision and narrowing in the mid-late 1980s in conjunction with a period of high precipitation. Thus, the historic pulse of invasion depended on both fluvial-geomorphic processes and climate, and was not directly linked to the timing of local plantings or flow regulation. In a similar study, Scott and Spence (2014) found that Russian olive established in bursts during the mid-1980s and post-1990s on the Escalante River, Utah despite being planted in the watershed during the 1950s. Its establishment occurred during the later phases of a period of channel narrowing that began in the 1950s and was dominated by cottonwood establishment. More research is needed to address the ecological and environmental factors driving the Russian olive invasion process.

RUSSIAN OLIVE IMPACTS

Nutrient dynamics. Several recent studies have documented effects of Russian olive on nutrient dynamics in riparian ecosystems. In particular, Russian olive leaf litter, perhaps in combination with leaf leachates and root exudates, can significantly increase riparian soil N pools. DeCant (2008) compared soils under sub-canopy Russian olives with those under only cottonwood canopy in riparian gallery forests on the Rio Grande, New Mexico. DeCant found elevated soil N levels under sub-canopy Russian olive trees, as well as greater soil organic matter accumulation. These effects occurred directly under the Russian olive canopy, and declined beyond the canopy edge. However, Russian olive did not appear to affect soil microbial activity, even when carbon limitation was removed with carbon additions. Further, foliar $\delta^{15}N$ values indicated that cottonwood did not utilize N fixed by sub-canopy Russian olive. In another study conducted in cottonwood gallery forests on the Rio Grande, Follstad Shah et al. (2009) found sub-canopy Russian olive leaf fall to be the strongest predictor of soil N levels across multiple study sites. Here, Russian olive leaf litter contributed 19 percent of N entering the riparian system from leaf fall despite it comprising only five percent of litter fall mass. However, Russian olive leaf fall did not predict potential rates of N immobilization or nitrification. According to the authors, this result was likely due to the fact that the C:N ratio of the Russian olive leaf litter and riparian soils were near the threshold value above which microbial activity switches from N mineralization to N immobilization (Follstad Shah, Harner, and Tibbets, 2009). Importantly, while Follstad Shah et al. (2009) worked at riparian sites where Russian olive was an understory species, its effect on soil N may be larger in settings where it is more abundant and/or dominant. Indeed, the impact of Russian olive on soil N varied with ecological context on the South Fork Republican River in eastern Colorado, with impacts strongest in meadow areas outside of the cottonwood gallery forest (Tuttle et al. in review). Russian olive plots that occurred under a cottonwood overstory had 1.7 times higher available soil N than reference plots located at least 3 m away from Russian olive. Russian olive plots in open areas, not under a cottonwood overstory, had 3.1 times higher available N compared to reference plots.

Russian olive has also been shown to affect nutrient dynamics in aquatic ecosystems at invaded sites. In general, riparian vegetation has the potential to influence aquatic ecosystems via shading, geomorphic and hydrologic effects, nutrient uptake and inputs, and organic matter inputs. Mineau et al. (2011) compared aquatic N dynamics at Russian olive invaded and un-invaded reference sites in Idaho and Wyoming, and found that sites with abundant Russian olive had higher stream organic N concentrations, reduced N limitation of biofilms, and higher demand for both NH_4-N

and NO$_3$-N. Thus, riparian Russian olive affected N dynamics in the adjacent aquatic ecosystem, though it appeared that added N could be retained rather than exported downstream.

Organic matter dynamics. Russian olive appears to increase soil organic matter pools in invaded terrestrial ecosystems and benthic organic matter pools in adjacent aquatic environments. DeCant (2008) observed thicker soil organic horizons under Russian olive trees growing in the understory of a cottonwood gallery forest compared to those growing under cottonwood alone. Mineau et al. (2012) found that riparian Russian olive provided a substantial allochthonous organic matter input to aquatic ecosystems at an invaded site in Idaho, and slow litter decay rates resulted in a dramatic increase to benthic organic matter pools.

Decomposition dynamics of Russian olive leaf litter differ from those of leaf litter of native species. In particular, the decomposition rate of Russian olive leaf litter is faster than that of native cottonwoods in terrestrial floodplain environments, but not in aquatic environments. Simons and Seastedt (1999) examined leaf litter decomposition rates of Russian olive and Plains Cottonwood (*Populus deltoides* ssp. *monilifera*) on a floodplain in the Colorado Front Range and found that Russian olive leaves decayed more quickly. In contrast, Royer et al. (1999) found that when submerged in a hardwater stream (Mink Creek, Idaho), Russian olive leaf litter decayed at the same rate as native Dogwood (*Cornus stolonifera*) and Aspen (*Populus tremuloides*) litter; and when submerged in a higher elevation, colder softwater stream (Big Wood River, central Idaho), Russian Olive decayed more slowly than black cottonwood (*Populus trichocarpa*) leaf litter. Similarly, Mineau et al. (2012) found that when submerged in Deep Creek, in southeast Idaho, Russian olive leaf litter decayed more slowly than that of a Peachleaf willow (*Salix amygdaloides*). Harner et al. (2009) compared Russian olive and Rio Grande Cottonwood (*Populus deltoides* ssp. *wislizeni*) leaf decomposition rates in terrestrial floodplain and submerged aquatic locations on the Rio Grande, New Mexico. They found greater mass loss rates of Russian olive leaf litter compared to cottonwood on the floodplain, but no difference in mass loss rates in the river channel. In addition, fungal biomass was greater on Russian olive leaf litter compared to cottonwood on the floodplain, but not in the river channel. The authors argued that differences between these results for the aquatic system and those of Royer et al. (1999) may have been due to differences in stream water chemistry between the two study streams.

Several factors likely contribute to the observed differences in decomposition rates of leaf litter across species (Russian olive vs. native species) and ecosystems (terrestrial vs. aquatic environments). In general, leaf litter decomposition rates are affected by physical environmental factors, litter quality, and the characteristics of the microbial community (Chapin, Matson, and Mooney, 2002). Physical factors influencing decomposition include temperature, moisture, and soil properties. Relevant aspects of litter quality include: (1) C:N ratio of the litter, with lower ratios expected to result in faster decay rates, (2) presence of recalcitrant compounds (e.g., lignin) in the litter, which are not readily decomposed, and (3) presence of allelochemicals, which inhibit microbial activity. Consistent with the faster decay rate of Russian olive leaf litter compared to that of native species observed in terrestrial environments, Russian olive leaf litter exhibits a lower C:N ratio than that of native cottonwoods and willows (Table 1). On the other hand, the slower decay rate of Russian olive leaf litter compared to that of native species in aquatic ecosystems may be due to the presence of recalcitrant compounds or allelochemicals that slow decomposition in aquatic ecosystems (Mineau et al., 2012; Moline and Poff, 2008). Moline

and Poff (2008) found that Russian olive leaves contained a higher percentage of structural carbon (i.e., lignin and "acid-soluble fraction", which includes cellulose and hemicellulose) than Plains Cottonwood leaves. It is not known why the relative foliage decomposition rates of Russian olive and Cottonwood differ between aquatic and terrestrial ecosystems. However, there is some indication that when decomposition rates are fast (i.e., in warm streams), inter-species differences are less likely to be observed (Harner et al. 2009, Royer et al. 1999).

Riparian hydrology and geomorphology. As an abundant woody plant in western U.S. riparian ecosystems, Russian olive has the potential to impact riparian water availability. Riparian water use, evapotranspiration, constitutes a significant source of water loss from rivers and riparian ecosystems in arid and semi-arid climates (Dahm et al., 2002). However, there exists little research addressing the water use or hydrologic impacts of Russian olive. Dahm et al. (2002) used micrometeorological towers to measure riparian evapotranspiration for a variety of vegetation types along the Middle Rio Grande, New Mexico. Dahm et al found that a mixed stand of mature cottonwood with a dense understory of Russian olive and tamarisk had the highest rate of annual evapotranspiration, compared to monotypic stands of cottonwood and tamarisk. Using satellite data, Allen et al. (2005) estimated whole stand Russian olive evapotranspiration on the Middle Rio Grande, New Mexico to be 1.4 m/yr. Gong et al. (2006) used a portable leaf chamber to measure water relations of Russian olive near the Linze Oasis, northern China, and found that Russian olive had high transpiration rates compared to three other desert species. Zhang et al. (2006) used a thermal dissipation probe to measure stem sap flow of Russian olive at the Ejin Oasis on the lower Heihe River, China, and estimated whole tree water use to be 2.43 L/day during the growing season. Hultine and Bush (2011) also provided stem sap flow data on whole tree water use, indicating that Russian olive had high water use compared to Fremont cottonwood near Salt Lake City, Utah. They argued that wherever Russian olive establishes within cottonwood gallery forest understories, it adds additional biomass and leaf area and therefore is likely to increase stand scale evapotranspiration. Overall, more research is needed regarding Russian olive water relations, water use, or impacts to ecosystem hydrology.

Riparian vegetation plays an important role in regulating fluvial geomorphology via processes such as bank stabilization, flow resistance, and sediment accretion (Simon, Bennett, and Neary, 2004). Russian olive is therefore likely to influence fluvial geomorphic processes along rivers where it is abundant, though there appear to be few studies addressing this impact. Reynolds et al. (2014) found no evidence that Russian olive and tamarisk establishment promoted sediment accumulation in riparian areas of Canyon de Chelly National Monument, Arizona. Rather, their establishment on the active floodplain may have facilitated the period of channel narrowing that occurred during the 1980s and 1990s, and may have also triggered the accompanying channel incision. Scott and Spence (2014) hypothesized a minor geomorphic role for Russian olive during the late stages of the period of channel narrowing on the Escalante River, Utah. As is the case for Russian olive eco-hydrology, more research is needed regarding the role of Russian olive in fluvial geomorphic processes.

Plant communities. There is a lack of published information about how Russian olive affects plant communities. Zouhar (2005) provided descriptions of vegetation types and plant communities in which Russian olive occurs in the United States. Russian olive tends to occur in two types of settings in western U.S. riparian areas – in the understory of cottonwood-willow

gallery forests, or in monotypic (or near-monotypic) stands on floodplains or in former riparian meadows or wetlands. Clearly, establishment of Russian olive at high densities alters riparian woody plant communities (Katz and Shafroth, 2003). However, little information exists about how Russian olive affects herbaceous plant communities. In Canyon de Chelly, Arizona, herbaceous plant communities under Russian olive had >60% exotic plant cover, including *Bromus tectorum* and *Bromus rigidus*, and <40% native plant cover (Reynolds and Cooper, 2011). Exotic cover, native cover, weighted wetland indicator score, and plant community composition differed between controls where Russian olive was left in place and where Russian olive removal treatments were administered, suggesting that Russian olive affects plant communities. In a recent study of Russian olive impacts, Tuttle et al. (in review) found a strong effect of Russian olive on understory vegetation at the South Fork Republican River in eastern Colorado. The understory vegetation contained distinct species composition, higher exotic cover, and altered functional composition of the plant community in plots under Russian olive compared to reference plots. This effect was mediated by ecological context with the strongest impacts occurring when Russian olive occurred in open areas and on particular fluvial geomorphic surfaces, but not under a cottonwood overstory. However, more research is needed on this topic.

Bird communities.[1] Several studies have found that Russian olive provides food and/or habitat for bird species, but is not functionally equivalent to native vegetation. Leatherman (2011) lists a variety of birds that consume fruits, sap, leaf aphids, and wood boring beetles from Russian olive in Colorado. Knopf and Olson (1984) compared avian densities among three habitat types, riparian native vegetation, Russian olive stands, and native upland vegetation, at sites in Colorado, Utah, and Idaho. Knopf and Olson found high bird abundance, but intermediate avian species richness and diversity, in Russian olive stands. Russian olive bird communities were somewhat similar to those of riparian forests, generally containing shrub nesting species but not the suite of obligate riparian species that require large trees. Nesting mourning doves (*Zenaida macroura*) and territorial yellow-breasted chats (*Icteria virens*) were recorded at especially high densities in the Idaho Russian olive stands. Similarly, along the Snake River in Idaho, Brown (1990) found a richness of intermediate breeding season avian species in Russian olive stands, compared to four structurally similar riparian habitat types (willow [Salix spp.], willow-Russian olive mix, river birch [*Betula nigra*], and hackberry [C*eltis reticulata*]). Community composition and guild structure differed among habitat types, with insectivores and cavity nesters generally absent from Russian olive stands. However, Fischer et al. (2012) found no influence of Russian olive proportion on bird density, species richness, or community composition within Russian olive dominated riparian habitats on the Snake and Columbia Rivers in southeastern Washington.

Research in New Mexico and Montana addressed the habitat role of Russian olive where it occurs in the understory of native dominated riparian gallery forests. Stoleson and Finch (2001) studied breeding-bird habitat use on the Gila River floodplain, New Mexico where Russian olive was a minor forest component representing 3.7% of woody stems >5 cm diameter. A total of 904 nests (<8 m high) were located for 29 bird species. Of these, 11 species placed 61 nests in Russian olive. Three species, mourning dove, yellow-breasted chat, and willow flycatcher (*Empidonax traillii extimus*), nested disproportionately more in Russian olive than in other

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[1] The section on avian use of Russian olive is adapted from Ratti (nd).

species of tree or shrub. Nest success did not differ between Russian olive and other nest sites. Yong and Finch (2002) examined migratory bird use of riparian stopover habitat patches, including cottonwood gallery forest with a Russian olive understory, but not monotypic Russian olive stands on the Rio Grande, New Mexico. They found high avian species richness and intermediate bird abundance in cottonwood/Russian olive patches compared to other patch types. Presence of understory Russian olive did not appear to have a strong influence on bird community composition. In contrast, Jones (2009) found that cottonwood forest patches with Russian olive dominated understories provided distinctive habitat for some bird species (e.g., least flycatchers [*Empidonax minimus*], red-eyed vireos [*Vireo olivaceous*]), while providing habitat similar to other cottonwood forest patch types for others (e.g., yellow warblers [*Dendroica petechia*], warbling vireos [*Vireo gilvus*]) on the Yellowstone River, Montana.

The effect of Russian olive on bird communities depends on ecological context. Where Russian olive occurs as an understory species in riparian gallery forests, it may affect forest habitat without fundamentally changing the ecosystem type or excluding species such as cavity nesters that rely on larger riparian trees. However, subtleties of habitat structure, including both overstory canopy density and characteristics of the Russian olive understory layer, will affect use of the habitat by specific bird species. For example, Jones (2009) argued that certain bird foraging and nesting guilds were suited to exploit cottonwood-Russian olive patches on the Yellowstone River, particularly species who forage and nest in the high canopy, or that forage in the high canopy and nest in the lower canopy. However, where Russian olive occurs in monotypic or near-monotypic stands, its invasion more substantially transforms ecosystems. For example, invasion into a grassland converts the ecosystem to a woodland or forest. This kind of shift can be expected to produce substantial changes to bird communities, likely excluding grassland birds, but providing substantial novel woody habitat, albeit habitat that is not functionally equivalent to riparian gallery forests. The nature of these shifts will depend on the species composition of bird communities present in the region, as well as the local spatial configuration and level of regional dominance of Russian olive in the riparian ecosystem (Fischer et al., 2012).

Other animals. Russian olive fruits, flowers, stems, leaves and leaf litter appear to support invertebrates, including native and exotic species. For example, Hinners and Hjelmroos-Koski (2009) found that wild bees in a fragmented Colorado landscape commonly carried Russian olive pollen in their pollen loads. Leatherman (2011) listed four aphid species of the genus *Capitophorus, C. braggii*, *C. shepherdiae*, *C. hippophaes,* and *C. eleagni*, observed on Russian olive leaves in Colorado, as well as two species of wood boring beetles, red-headed ash borer, (*Neoclytus acuminatus*) and oak twig pruner, (*Analaphus parallelus*) observed on Russian olive stems. Royer et al. (1999) observed similar numbers of biomass, and community composition of invertebrates on submerged leaf packs of Russian olive and cottonwood on the Big Wood River, Idaho. In a laboratory setting, Moline and Poff (2008) found that larvae of a large aquatic invertebrate shredder (crane fly, *Tipula* sp.) survived well on Russian olive leaves, supporting densities similar to those observed on native cottonwood leaves. Heinzelmann et al. (1995) observed similar abundances of the exotic terrestrial isopod *Armadillidium vulgare* in pitfall traps associated with leaf litter of Russian olive and cottonwood on the Rio Grande floodplain, New Mexico. However, in laboratory experiments, *A. vulgare* exhibited higher growth and survival on Russian olive litter (Heinzelmann et al., 1995). In a follow up study, Abelho and Molles (2009) examined feeding preferences of *A. vulgare* collected from the Rio Grande

floodplain, New Mexico. In both multiple-choice and no-choice laboratory feeding experiments, isopods generally exhibited the highest consumption rates of Russian olive fruits and green Russian olive leaves compared to senesced Russian olive leaves, senesced cottonwood leaves, and fresh cottonwood leaves. However, contrasting food sources did not result in differences in isopod biomass increase during the experiment. Collette (2014) compared arthropod communities associated with Russian olive, with those associated with co-occurring species of similar growth form: Woods' rose (*Rosa woodsii* Lindl., Rosaceae) and Saskatoon *(Amelanchier alnifolia* Nutt., Rosaceae) in south-central British Columbia, Canada. Using standardized sampling methods, Collette (2014) found that insect family diversity, richness, and composition did not differ between Russian olive and the other two plant species, and insect abundance associated with Russian olive was intermediate between that of rose and Saskatoon. Collette concluded that Russian olive produced neutral impacts to insect communities in the study area.

Russian olive also provides food and shelter for some vertebrate species. For example, Russian olive seeds were subjected to high rates of granivory in a rural agricultural setting near the foothills of the Colorado Front Range, likely consumed by rodents such as deer mice (*Peromyscus maniculatus*) and house mice (*Mus musculus*) (Katz et al., 2001). On the other hand, Russian olive does not appear to provide a suitable wood source for beavers (*Castor canadensis*) along rivers in Montana (Lesica and Miles, 2004).

SUMMARY AND CONCLUSIONS

General conclusions and research needs. The scientific literature on Russian olive has grown considerably since the Stannard et al. (2002) and Katz and Shafroth (2003) reviews were written. For example, there has been progress on identifying Russian olive impacts to nutrient cycling and organic matter dynamics, and a number of studies have addressed avian use of Russian olive. However, more research is needed to better understand the dynamics and impacts of Russian olive invasion in western U.S. riparian ecosystems. Nagler et al. (2011) identified several key data needs and research gaps with respect to Russian olive. These included (1) assessments of positive and negative effects of invasion, (2) fine scale inventories and studies of environmental factors that influence Russian olive abundance, e.g., flow regime, salinity, and degree of disturbance, (3) better studies and models of the Russian olive invasion process, and (4) predictions of the effects of climate change on Russian olive distribution. It appears that all of these research needs remain relevant.

Based on this literature review, a few priority areas stand out as needing increased research attention. First, more studies addressing the invasion process are needed to identify the drivers and limitations of Russian olive spread. Second, better elucidation of the impacts of Russian olive invasion on ecological communities are needed as there is little published information about effects on plant communities or animals other than birds. While we have made progress in understanding Russian olive impacts to abundance and diversity in avian communities, little is known about impacts to productivity. More research is needed to compare food availability, predator abundance, and survival and reproductive success of birds across a range of Russian olive native dominated habitats (Fischer et al., 2012). Similarly, more research is needed to address the habitat and food value of Russian olive for arthropods (Collette, 2014). Third, little is known about Russian olive water relations or potential impacts of its invasion to water resources

(Hultine and Bush, 2011), as well as the geomorphic role of Russian olive. An improved understanding of these topics will allow better predictions of Russian olive invasion into new areas, and better assessment of how Russian olive affects valued aspects of riparian ecosystems. This understanding will enable more targeted management approaches that focus on ecosystems or habitats of greatest concern.

Russian olive management. Efforts are underway to control Russian olive throughout the western U.S. (O'Meara, Larsen, and Owens, 2010). Control typically entails mechanical removal coupled with cut-stump herbicide application. Projects range in size from isolated site level removal projects to larger integrated river or watershed scale eradication efforts. Russian olive control efforts are motivated by a variety of concerns including water salvage and habitat restoration. However, not all stakeholders agree that Russian olive removal from riparian areas is warranted, especially considering its wildlife value. Further, because Russian olive is appreciated as a component of urban, suburban, and rural landscaping and windbreaks, it is unlikely that its complete eradication is a feasible management objective from a social perspective.

Although exotic plant removal is a common management strategy in natural ecosystems worldwide, the published literature does not strongly confirm the benefits of this approach for native plant communities. In a literature review of weed management efforts in Australia, Reid et al. (2009) found that only 18 of 95 papers reported post-removal changes to associated plant communities, while three papers reported changes to invertebrate communities. In these studies, native plant communities did not necessarily recover following exotic plant removal because re-invasion or invasion by novel invaders was often an issue. Similarly, Kettenring and Adams (2011) conducted a systematic review and meta-analysis of 355 invasive plant removal research papers of which 84 papers reported treatment responses of native and/or exotic species. In general, exotic plant removal treatments resulted in reduced cover, biomass, and density of exotic species, but had little impact on natives. The authors argued that this result could be at least partly due to propagule limitation of native species, and that active native re-vegetation may be a necessary component of restoration following exotic plant removal. In general, more research is needed to assess how exotic plant removal treatments impact extant native plant communities and establishment of native species, and how active re-vegetation treatments affect recovery trajectories. Importantly, 52 percent of the studies reviewed by Kettering and Adams (2011) monitored vegetation responses for <1 year suggesting a need for longer term monitoring of treatment responses. These research needs apply directly to the case of Russian olive removal in the western U.S., where many removal projects are underway.

As in the case of tamarisk control (Sogge, Paxton, and van Riper III, 2013), Russian olive removal is likely to have profound consequences for ecosystem processes and wildlife. Like tamarisk, Russian olive is currently a major structural and ecological component of many western U.S. riparian areas that play a key ecological role. Short-term effects of Russian olive removal will depend upon removal timing, spatial extent, and methods used. Long-term effects will depend upon the pattern of ecosystem response, including establishment of native plant communities and/or re-invasion by Russian olive or other exotic species. Paxton et al. (2011) described a conceptual model of short- and long-term effects of tamarisk biocontrol, which predicted effects on bird communities depend upon the recovery of native riparian woodland vegetation. If native woodland recovery results in no net loss of riparian habitat, then a positive

influence on bird populations is predicted. On the other hand, if native woodland recovery is not sufficient to compensate for the loss of tamarisk, then the net loss of riparian habitat will result in decreased bird populations. In their model, replacement of tamarisk by non-woody vegetation is likely to produce negative effects to birds. The issue of native vegetation recovery is highly relevant to management of Russian olive, which has become established in many floodplain environments where native woody riparian vegetation does not occur (e.g., herbaceous wetlands, floodplain meadows). Without restoration plantings, its removal from these habitats is likely to result in establishment or re-establishment of non-woody plant communities.

A variety of approaches and goals can be considered with respect to management of Russian olive in western U.S. ecosystems. However, such approaches should be based on a sound understanding of the ecological role of Russian olive, and on realistic projections of management outcomes. For tamarisk, Sogge et al. (2013) presented a nuanced approach to management, providing an instructive list of guidelines based on current scientific understanding of its ecological role in western U.S. riparian ecosystems. Though all are valuable, the following guidelines are of particular relevance to managing Russian olive: (1) recognizing that control will benefit some species and harm others, (2) balancing removal with native habitat restoration, both geographically and over time, and (3) managing some riparian areas for mixed native-exotic habitat, rather than total elimination of the exotic species. For example, Sogge et al. (2008) suggested that selective mechanical or herbicidal removal of tamarisk would allow managers to reduce the ecological risks associated with broad scale loss of tamarisk habitat and gradually convert vegetation from tamarisk to native in order to ensure continuous availability of high quality riparian habitat over time. Sogge et al. proposed that managers could remove tamarisk from selected sites or remove only a portion of tamarisk from a given site. van Riper III, et al. (2008) identified a threshold in the effect of vegetation composition on bird densities in tamarisk-dominated habitats on the lower Colorado River, Arizona. In tamarisk-dominated habitats, those with 20-40 percent native vegetation had a higher abundance of birds, and they noted a, continuing positive effect on the bird community as the percent of native vegetation increased. The highest bird abundances occurred in areas of mixed native-exotic woody vegetation. They attributed this pattern to the increased structural complexity provided by tamarisk in mixed vegetation stands, and to the possible enhancement of food availability by tamarisk in these areas. Thus, the authors argued that restoration of relatively small areas of native vegetation within tamarisk-dominated habitats would have a disproportionally positive effect on avian communities, creating an efficient and effective management option that did not necessitate tamarisk eradication.

More research is needed to examine the ecological role of Russian olive across a range of densities, ecological contexts, and spatial configurations within western U.S. riparian ecosystems. Such information is needed to inform Russian olive management and riparian restoration strategies. For example, Fischer et al. (2012) found a threshold response of bird communities to habitat characteristics in Russian olive dominated habitats on the Snake and Columbia Rivers, Washington. Here, bird density and species richness peaked at 50-70 percent total woody vegetation cover, indicating that complete eradication of Russian olive would likely produce detrimental effects. Instead, they suggested that spatial heterogeneity in habitat conditions may best provide resources for a diversity of bird species in ecosystems dominated by Russian olive, and

that maintaining 50-70 percent total woody vegetation cover, even if dominated by Russian olive, was an appropriate management goal.

Following Russian olive removal, additional treatments may be needed to achieve desired management outcomes. That is, removal of Russian olive alone does not necessarily constitute 'ecological restoration', and additional steps may be needed to replace Russian olive with desired vegetation or to achieve more natural system form and function (Kettenring and Adams, 2011; Reid et al., 2009; Shafroth, Merritt, Beauchamp, and Lair, 2010; Shafroth et al., 2013). For example, Harms and Hiebert (2006) compared vegetation at 33 sites in the southwestern U.S. where tamarisk had been removed 1-11 years previously to control sites where tamarisk was untreated. Harms & Hiebert found negligible differences in plant species richness, diversity, and community composition when tamarisk was not included in the analysis. Despite 82-95 percent reductions in tamarisk foliar cover, native plant establishment appeared to have been inhibited at treated sites, possibly due to long standing drought conditions or to lack of available seeds (Harms and Hiebert, 2006). Thus, additional treatments were likely needed in order to improve wildlife habitat and to push riparian vegetation to desired trajectories. Post-removal restoration treatments may be passive (e.g., removing stressors, and/or restoring physical conditions such as hydrology) or active (e.g., site grading, seeding, transplanting). Where it is possible, passive restoration is a preferable approach to restoration, since it is more likely to be successful in the long term and over large spatial scales (Shafroth et al., 2013). However, in all cases ecological site factors including valley and bottomland geomorphology, surface and groundwater hydrology, soil chemistry and texture, and characteristics of extant vegetation (including propagule availability), will strongly constrain the possible restoration outcomes at a given site (Shafroth et al., 2013).

It is unknown whether revegetation is an important or effective component of long-term ecological restoration following Russian olive removal. Several authors have argued for the importance of revegetation following tamarisk removal (Bay, 2013; Harms and Hiebert, 2006), and following exotic plant removal in general (Kettenring and Adams, 2011). Revegetation efforts can include soil preparation, transplanting of rooted plants, pole planting, and seeding (Shafroth et al., 2013). The species used for revegetation should be appropriate for site conditions, including hydrology and soils (Bay 2013). In addition, irrigation may be needed to promote establishment of planted and seeded species. The purposes of revegetation may be to improve wildlife habitat, increase richness and cover of desired native plant species, reduce rates of reinvasion by the targeted exotic species, and reduce erosion (Kettenring and Adams 2011, Bay 2013). In the case of tamarisk removal, revegetation is likely to inhibit tamarisk reinvasion because tamarisk seedlings are poor competitors (Bay 2013). However, the ecology of Russian olive presents a significant contrast to that of tamarisk, and raises questions about the long-term effectiveness of revegetation in preventing reinvasion. In particular, because Russian olive is shade tolerant, can establish in the absence of disturbance, and can create a considerable soil seed bank at invaded sites, it is unlikely that revegetation will prevent Russian olive reinvasion at treated sites entirely. On the other hand, revegetation could achieve other management goals, such as accelerated creation of wildlife habitat and prevention of erosion. More research is needed to assess the role of revegetation in Russian olive management projects.

POINTS OF CONTACT: For additional information, contact Dr. Richard A. Fischer (502-641-7824), *Richard.A.Fischer@usace.army.mil*) or the manager of the Ecosystem Management and Restoration Research Program, Glenn Rhett (601-634-3717, *Glenn.G.Rhett@erdc.usace.army.mil*). This technical note should be cited as follows:

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